MONITORING OF BIOGAS EMISSIONS FROM AN URBAN LANDFILL BY MEANS OF CLOSE-RANGE AERIAL INFRARED THERMOGRAPHY

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Abstract

Monitoring waste disposal sites is important to check that the produced biogas, potentially explosive and environmentally significant, is properly collected by the biogas extraction system of the landfill site and to evaluate the residual biogas flow escaping from the upper surface of the landfill. As the biogas migrates to the surface, the soil through which it flows is expected to reach a higher temperature than the surrounding environment; thus, measuring the thermal footprint of the landfill soil surface could allow the detection of biogas leakages and spots suitable for gas extraction. Infrared thermography is an innovative diagnostic tool able to detect thermal anomalies on the landfill surface. If the infrared camera is installed on an unmanned aerial vehicle, thermal anomalies can be identified with a good resolution over a large region. A simple procedure to deduce the biogas flow rate emerging from the soil into the atmosphere, based on infrared thermography measurements, is presented. The approach has been applied to a case study concerning a large landfill located in Genoa, northern Italy. Aerial infrared photographs taken during different days and seasons showed the presence of thermal anomalies over regions along the peripheral boundary of the landfill still not interested in biogas extraction.

1 Introduction

Municipal solid wastes disposed in landfills contain a significant percentage of organic substances whose degradation produces a large amount of biogas with high methane content. Part of the methane can be captured and used as a renewable energy source to generate heat and/or electricity. Few landfills are thought to recover more than 60% of the available gas [1]; the rest is allowed to escape to the atmosphere, with a not negligible global warming potential. Biogas leakages have a large impact on the environment even at a local scale, due to risks of explosions, odour, and adverse effects on human health and vegetation. The landfill biogas is a product of anaerobic digestion of organic compounds and this reaction is accompanied by release of heat. As the biogas migrates to the surface, the soil through which it flows is expected to reach a higher temperature than the surrounding environment. Measuring the thermal print of the landfill soil surface could enable the detection of biogas leakages and spots suitable for the gas extraction. In principle, the evaluation of the flow rate of the biogas emerging from the soil into the atmosphere can be deduced from a steady-state heat balance. The thermal power produced by digestion is dissipated to the environment by radiation, convection and conduction; thus, heat transfer dissipated to the environment is basically a function of heat transfer surface area and the soil surface temperature.

Infrared thermography (IRT) is an innovative diagnostic tool able to detect thermal anomalies on the landfill surface. It constitutes a non-invasive technique that registers the temperature distribution by means of a thermal camera that receives and processes the infrared radiation emitted from the target surface. A first review of application of IRT to monitor waste disposal sites has been provided by Lewis et al. [1], where most of the mentioned previous studies concerned the use of ground based infrared (IR) cameras. Aircraft-mounted cameras improve the potential of the technique, since a large area can be monitored in a relatively short time [2−5]. The use of unmanned aerial vehicles (UAVs) represents the added value to the thermographic inspection of waste disposal sites. In fact, airborne IRT might miss smaller scale leaks due to large distances from the target. Conversely, UAVs permit to vary the scale of the imaging by properly arranging the distance between the UAV and the target (typically from 10 to 70 m) in order to provide an adequate resolution of the surface thermal map. Moreover, the IR camera mounted on UAVs operates in ideal conditions with the sensor perpendicular to the target, contrary to what happens when infrared images of the landfill surface are taken directly from the terrain, with a viewing angle largely away from the normal direction and a markedly increased uncertainty in the measurement. The IR camera, mounted on UAVs, is typically synchronized with the position log of the UAV navigation system and with a built-in visual camera in order to obtain the precise thermal mapping of the landfill.

Limitations in use of IRT to detect gas leakages from landfills are outlined in [1]: results may be significantly affected by weather and soil conditions. Windy and warm days are usually not indicated as well as the presence of surface wetness or different types of ground materials; all these factors could give rise to anomalies without connections to landfill gas leakage or dilute the associated thermal anomaly. On the contrary, night-time surveys reduce light condition influences while cloudy conditions mitigate the effect of the sky radiation. It is apparent that the variability of environmental conditions (e.g., air temperature and solar/sky radiation) and of the observed targets (e.g., modifications in the soil coverage and vegetation) makes quantitative IRT a non-trivial issue, requiring specific expertise by the user as well as an analysis performed in comparative terms (i.e., by looking at differences between targets with known radiometric properties and targets under study). Combination of different techniques, in order to get more elements for the interpretation and validation of results by cross-checking the information, is also advisable [6].

2 Methodology

2.1 Principles of Infrared Thermography

Infrared thermography is a two-dimensional, non contact technique for measuring surface temperature of solid objects. An infrared camera detects the electromagnetic energy radiated by the target within a given infrared spectral band (λ = 3-6 μm or 8-12 μm, depending on the employed optics) and converts it into an electronic video signal related to the surface temperature map of the target. The radiation sensor, which absorbs the infrared energy and converts it to a signal, can be either a photon detector or a thermal detector. The former has a higher sensitivity but it requires to be cooled well below the ambient temperature, the latter is less sensitive but cooling is not needed. Among the thermal detectors, uncooled microbolometers are small, lightweight and relatively cheap sensors and their advent made infrared thermography a very popular diagnostic tool, nowadays successfully exploited in a wide range of engineering applications (buildings, agriculture, medicine, and so on).

Radiant energy flux $E_{\lambda,b}$ [W/m^2·μm] from blackbody is given by the following relationship

$$E_{\lambda,b} = C_1 \lambda^{-5} / \left(e^{C_2/\lambda T} - 1 \right) \tag{1}$$

where C_1 and C_2 are radiation constants, λ is the wavelength, and T is the absolute temperature of the surface. A real object emits a fraction of the energy emitted by a blackbody at the same temperature and wavelength, on the basis of its surface spectral emissivity ε_λ. Generally speaking, the energy flux E_λ' detected by the IR camera is affected also by the environmental conditions, as follows [7]

$$E_\lambda' = \tau_{\lambda,atm}\, \varepsilon_\lambda\, E_{\lambda,b} + \tau_{\lambda,atm}\, (1 - \varepsilon_\lambda)\, E_{\lambda,\, amb} + (1 - \tau_{\lambda,atm})\, E_{\lambda,\, atm} \tag{2}$$

where $E_{\lambda,amb}$ is the energy flux corresponding to a blackbody at the temperature T_{amb} of object surroundings (the so-called reflected or background temperature), $E_{\lambda,atm}$ is the energy flux corresponding to a blackbody at the temperature T_{atm} of the atmosphere, and $\tau_{\lambda,atm}$ is trasmissivity of the atmosphere between the surface and the camera. Values of ε_λ and $\tau_{\lambda,amb}$ (for the range of wavelengths of interest) and of temperatures T_{amb} and T_{atm} have to be properly selected in order to derive, from the measured energy flux E_λ', the surface temperature of the target through Eq.(2).

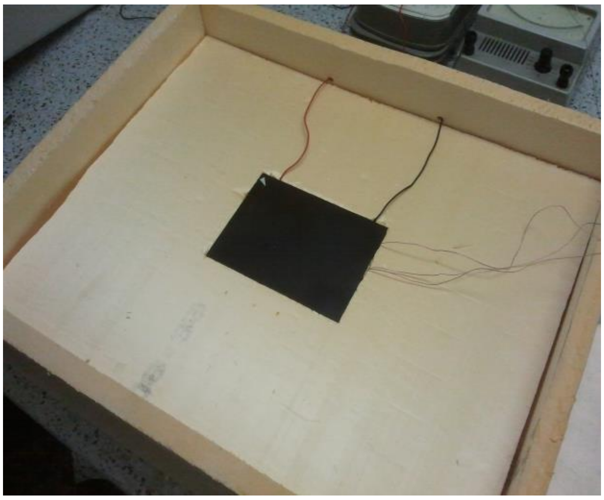

Fig 1 The container simulating a landfill with biogas production: the thermal source (top) and the covering sand layer (bottom)

2.2 Monitoring of Waste Disposal Sites

The digestion process to produce biogas is accompanied by a release of heat. This thermal power is dissipated to the environment by radiation, convection and conduction. Assuming for the sake of simplicity steady-state conditions and neglecting thermal conduction, the energy balance is given by the following equation

$$Q = \sigma\, \varepsilon\, A\, (T_w^4 - T_{surr}^4) + h\, A\, (T_w - T_{air}) \qquad (3)$$

where T_w [K], T_{surr} [K] and T_{air} [K] are the temperatures of the soil surface, the surroundings, and the ambient air, respectively, σ (=5.67 ×10^{-8} W/m^2·K^4) is the Stefan-Boltzmann constant, ε is the total hemispherical emissivity of the soil, h [W/ m^2· K] is the convective heat transfer coefficient and A [m^2] is the soil surface area. In Eq.(3), the first term on right-hand side represents the heat transfer rate from the soil surface to the surroundings by radiation (evaluated assuming an enclosure formed by a gray body at emissivity ε surrounded by a very large surface), while the second term is the convective heat transfer rate from the soil surface to the environmental air. In order to identify the heat transfer rate associated with the biogas production, the surroundings and the ambient air temperatures can be replaced by the undisturbed soil temperature $T_{w,ref}$ [K], as follows

$$Q = \sigma\, \varepsilon\, A\, (T_w^4 - T_{w,ref}^4) + h\, A\, (T_w - T_{w,ref}) \qquad (4)$$

Literature empirical equations, which take into account the effect of wind, can be used for the convective heat transfer coefficient h. For instance, the following equation, taken from [8], can be assumed for h

$$h = 5.7 + 3.8\, V \qquad (5)$$

where V is the wind velocity [m/s].

As the soil emissivity ε is a known parameter, typically assumed to be 0.9-0.95, the heat produced by digestion and dissipated to the environment is basically a function of heat transfer surface area A and the soil surface temperatures T_w and $T_{w,ref}$. Dividing Q by the heat associated with the production of methane (about 7325 kJ / m^3, [2]) leads to the estimation of the methane flow rate reaching the soil surface. The calculated methane flow rate from the above procedure is just a rough estimation due to the assumptions done in Eq.(3); weather conditions may induce not-steady surface temperature distributions, uneven material properties (surface emissivity and thermal conductivity) may affect the energy balance as well. Moreover, small gas leakages flowing through long pathways to reach the surface could not be recognized since insufficient to maintain the soil at a surface temperature relatively higher than that of the undisturbed soil.

3 Results

3.1 Test Case for Validation

A simple experiment has been designed in order to validate the previously described procedure. An aluminum plate (150 mm × 110 mm, thickness 8 mm), connected to an electric plane heater on the bottom side, has been placed inside a large container (400mm × 500 mm) made of 20mm-thick extruded polystyrene, as shown in Fig.1. The container has then been filled with a 10mm-thick sand layer. Several fine-gauge thermocouples have been placed inside the heated plate and along the sand layer. Once electric power is delivered to the heater, the plate, at steady-state, attains a uniform temperature value, detected by thermocouples and controlled by the DC power supply. The surface temperature of the sand is then detected by an infrared camera (FLIR T335, 320 x 240 pixels) assuming a thermal emissivity ε for sand of 0.95. Experiments were conducted in a laboratory room with ambient and wall temperatures equal to 26.5 ± 0.3 °C, without air currents (V=0 m/s in Eq.5). The delivered electric power, measured by means of a voltmeter and an amperometer, was adjusted in order to maintain a prescribed temperature difference between the plate and the ambient air.

A preliminary experiment has been conducted to evaluate the heat conduction losses from the container polystyrene walls. The sand layer facing the ambient air was covered by a 20mm-thick polystyrene layer in order to inhibit any convection and radiation heat transfer from the sand surface. At the steady-state, a thermal power of 1.6 W was dissipated by the heater to maintain a uniform temperature of 53°C over the aluminum plate (ambient air temperature equal to 26.5°C). Due to the symmetrical arrangement of the insulation layers, it was assumed that an equal quantity of 0.8 W has been dissipated by thermal conduction across the bottom and the top insulation layers. Once the top insulation layer was removed (thus allowing convective and radiant heat exchanges between the sand surface and the surroundings), the dissipated thermal power required to maintain the same temperature (53°C) over the heated plate was 5.1 W. If the conduction losses (0.8 W) through the bottom insulation layer are subtracted, the convective and radiant heat transfer rate Q_{meas} from the sand surface to the surrounding was measured to be 4.3 W.

Figure 2 displays the thermal map of the sand surface under the above described conditions. Two different areas have been identified: the larger one (Ar1) encompasses the entire thermal anomaly registered by the IR camera, the smaller one (Ar2) includes the surface region where the surface temperature is significantly higher with respect to boundaries. The imaging process has been performed using a dedicated software for thermal images elaboration (Flir QuickReport©, FLIR Systems) and Eq.(3) for the estimation of heat transfer rate. Results for the two regions of interest identified were:

Ar1) Q_{calc} = 4.6 W (52% radiation, 48% convection)

Ar2) Q_{calc} = 3.5 W (53% radiation, 47% convection)

By comparing the calculated heat transfer rates (Q_{calc}) with the measured one (Q_{meas} = 4.3 W), it can be argued that the heat transfer rated from the sand surface is correctly estimated (within a 7% error) by averaging the wall temperature over the region of area Ar1 and it is slightly underestimated (by 19%) when a smaller area (Ar2) is used for the analysis. Further experiments performed by varying the heated plate-to-ambient temperature difference (from 17 to 35 K) and the thickness of the sand layer (from 1 to 2.5 cm) gave rise to similar qualitative results, i.e., an agreement within 20% between the heat transfer rate from the sand surface to the environment based on the measurement of dissipated electric power and that deduced by IR imaging over a significant surface area.

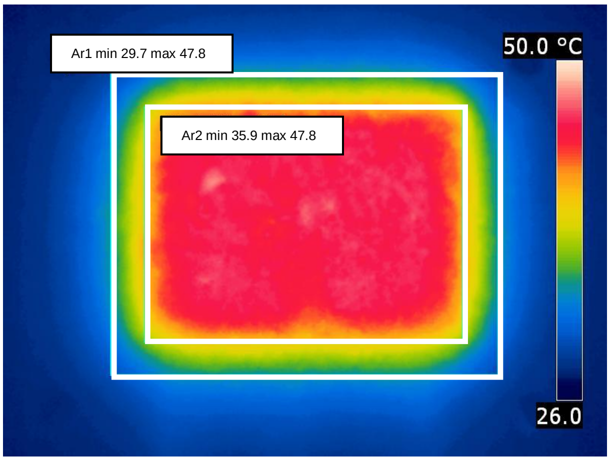

Fig.2 Surface temperature map of the sand, provided by the IR camera, for the simulated landfill experiment

3.2 Close-range Aerial IR Inspection of a Landfill Site

The main purpose of this study was to outline a procedure to detect and possibly quantify biogas emissions from the soil of a waste disposal site. To accomplish this task, several flights with UAVs equipped with infrared and visual cameras have been performed over the non-hazardous landfill of Mount Scarpino, located in Genoa, northern Italy and one of the widest European mountain landfill. This landfill, covering approximately an area of 58 hectares, has been used to dispose and manage the solid waste of the town of Genoa and its province for over forty years. A landfill gas power plant has been operating on site since 2007. The biogas (with methane concentration at 50% by volume) actually extracted from this site is about 50×10^6 m^3 per year, giving rise to an electrical energy production of about 65×10^6 kWh per year, saving more than 300.000 tons/year of CO_2.

Figure 3 shows an aerial image of the investigated landfill: the figure reports the distribution of wells and pipes for the biogas extraction. The investigation was conducted by performing several UAV flights over a period from February 2015 to March 2016, using different IR cameras and namely FLIR T460 (320 x 240 pixels), FLIR A65 (640 x 512 pixels), and FLUKE Ti 300 (240 x 180 pixels). Dedicated software programs (Flir Reporter Professional©, Flir Systems and SmartView©, Fluke Corporation, depending on the type of IR camera employed) and Eq.(4) were used to process the experimental data. At a 70m distance between the UAV and the soil surface, the spatial resolution was about 10 cm. A custom-made procedure has been developed to synchronize the thermal image with the visible image taken by a built-in optical camera and the position log of the UAV navigation system. To improve the precision of the thermal mapping of the landfill, some ground control points were detected in the thermal images. The maximum planimetric error associated with the procedure was estimated to be 0.4 m.

Flights were performed under different environmental conditions: in the mornings of one day of February 2015 and one day of August 2015 (both with clear sky), and during the late evening (without solar radiation) of two different days in the month of March 2016.

Environmental conditions (ambient air temperature and relative humidity, wind velocity) were detected by a local weather station. For all cases, wind was moderate (typically 5 m/s or less) and the terrain was dry, except for one of the flights performed in March 2016, when the site was wet and muddy in some spots.

Aerial thermographic inspections of the landfill along some peripheral regions still not interested in biogas extraction (sites No.1, 2 and 3 of Fig.3) have been performed and results have been processed in order to identify residual biogas superficial emissions and to infer, through a thermal balance, a rough estimation of the amount of escaping biogas flow rate. The investigated sites showed thermal anomalies occurring during all the flights. Since the flights performed in March 2016 were featured by the most suitable conditions for aerial thermographic investigation (low ambient temperature, no direct solar radiation), only data acquired during these flights were processed, whereas those recorded during the morning flights (with direct solar radiation) were considered only for a qualitative comparison of the thermal footprints over the sites of interest.

Infrared and visible images taken during the flight were matched by a custom-made software to produce a mosaic image giving at the same time the topographic view and the thermal map of the inspected sites, as shown in Figs. 4−6. In each figure, only surface temperature data exceeding by more than about 2°C the minimum surface temperature were displayed in coded colours.

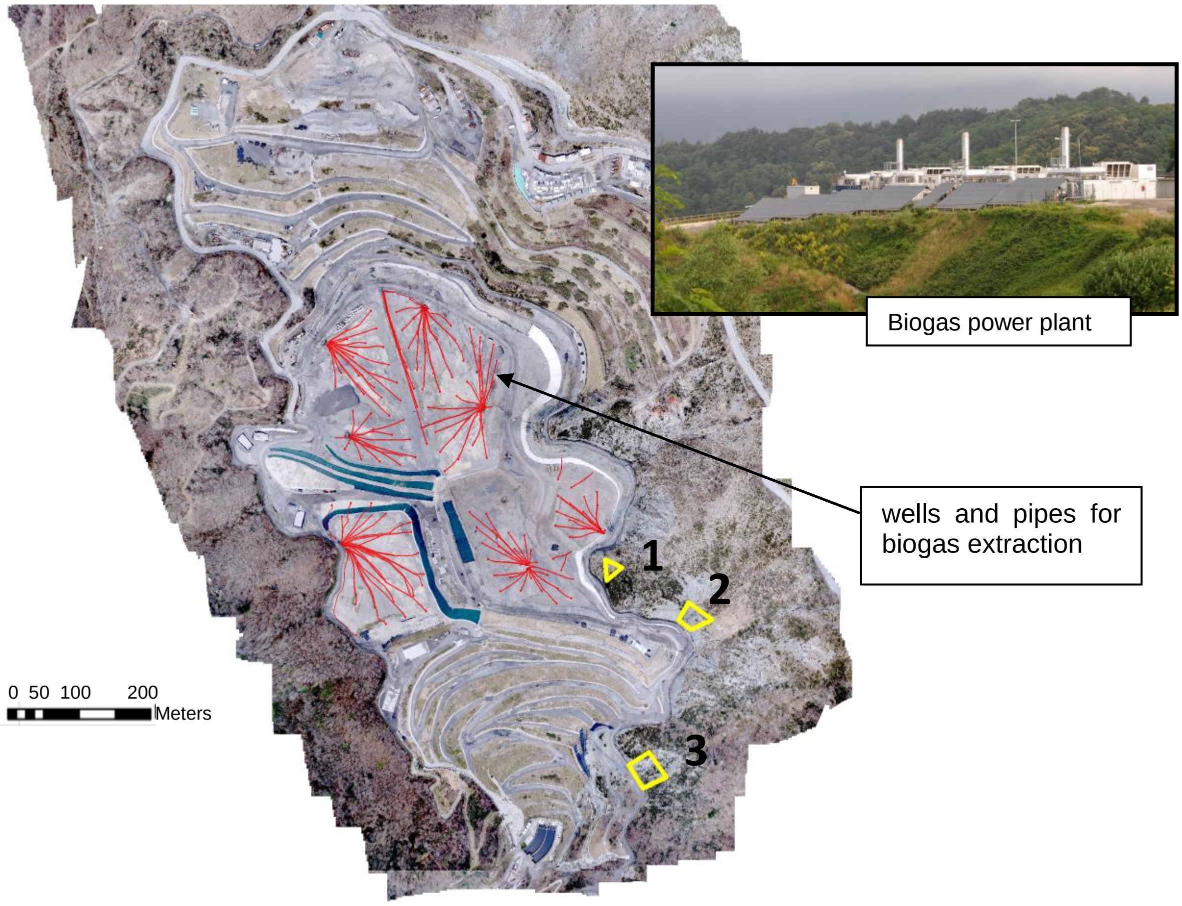

Fig.3 Topographic view of the landfill. Wells and pipes for the biogas extraction as well as the inspected sites (No.1, 2, and 3) by aerial infrared thermography are reported

Inspection of Figs. 4−6 reveals that marked thermal anomalies were present over the three specific investigation areas. Namely, surface area framed within the boundaries of site No.1 registered a temperature ranging from 3.5 to 10.3°C (average 5.2°C), area of site No.2 showed a surface temperature between 4.2 and 14.1°C (average 8.4°C) and site No.3 was featured by a surface temperature from 4.2 and 13.3°C (average 7.4°C). Table 1 reports the estimated heat flux associated with the biogas digestion from each site and the relevant methane flow rate actually dispersed into the atmosphere. Repeated measurements over the same sites by using different images captured during the same flight or comparisons among measurements over the same site by processing data taken in different flights revealed differences in the estimated methane flow rate within ± 30%. This figure can be realistically assumed as the uncertainty of this method, whose order of magnitude is comparable to that reported in similar studies [9] or associated with other measurement techniques, such as the tracer method or the static chamber method [10]. Taking into account the relatively large estimated uncertainty in the measurement, the amount of methane escaping from the inspected sites was found to be comparable to that actually collected by the existing wells and pipes conveying the extracted biogas to the thermal power station for energy conversion. The conducted analysis allowed the site manager to improve suction performance of the biogas system so that uncollected flows could be reduced.

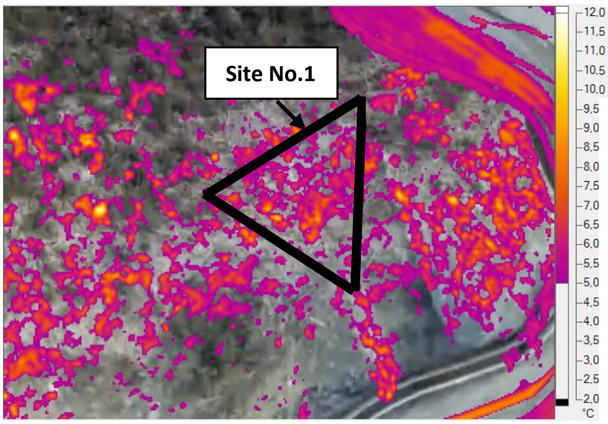

Fig 4 Thermographic data gathered for site No.1

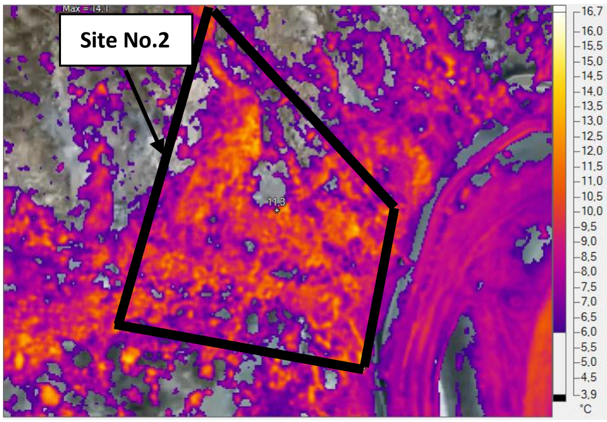

Fig 5 Thermographic data gathered for site No.2

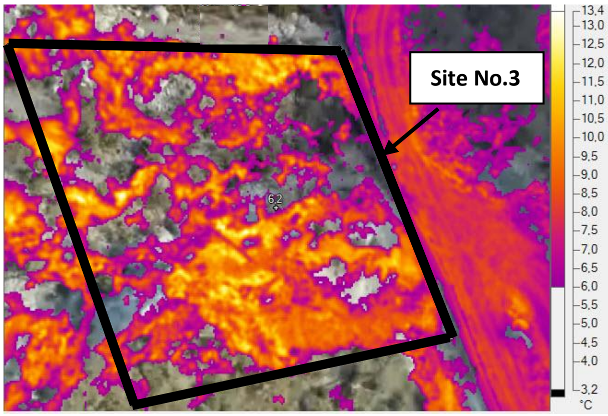

Fig 6 Thermographic data gathered for site No.3

Table 1. Estimated methane flow rates and main parameters included in the calculation procedure

	Site No.1	Site No.2	Site No.3
Surface area [m^2]	350	960	1500
Mean T_w [K]	278.3	281.5	280.5
Undisturbed soil temperature $T_{w,ref}$ [K]	277.6	277.3	277.3
Measured wind velocity V [m/s]	5.0	5.0	5.0
Imposed surface emissivity	0.95	0.95	0.95
Heat transfer rate [kW] by Eq.(4)	17.4	118.5	141.0
Estimated methane flow rate per m^2 [m^3/ h·m^2]	0.0245	0.0607	0.0462

4 Conclusions

Infrared thermography (IRT) has been applied to the study of biogas leakages from waste disposal sites. This diagnostic tool permits the identification of thermal anomalies on the landfill surface related to the biogas digestion processes and quickly allows the site manager to improve biogas suction system in well identified areas of the site. The implementation of this technique, whose applications in landfills documented in the literature are mainly based either on ground or aircraft inspections, consists in the use of unmanned flight vehicles (UAVs) to take IR images of the landfill surface. The close-range aerial inspection permits the gathering of data over a large region and at the desired spatial resolution by properly arranging the distance between the UAV and the investigated soil.

A simple calculation procedure, based on the steady-state energy balance between the heat produced by the digestion and the heat dissipated into the atmosphere, capable to provide to a rough estimation of the methane flow rate escaping from the landfill surface, has been presented. This monitoring technique allows a rapid check of wide surfaces that other detection tools (i.e., tracer or chamber methods) do not allow in comparable times.

The proposed method has been successfully applied to a case study concerning a large landfill located in Genoa, northern Italy, from which an amount of biogas of about 50×10^6 m^3 per year is currently extracted. Aerial infrared photographs taken during different days and seasons showed the presence of thermal anomalies associated with biogas digestion over regions along the peripheral boundary of the landfill and revealed for these sites the potential for significant amount (from 2.5 to 6 $\times10^{-2}$ m^3/ h per m^2 of surface area) of biogas extraction. Despite the limitations of the technique described throughout the paper, this study shows that close-range aerial IRT constitutes a reliable approach for monitoring urban landfills with a wide application market. The presented calculation procedure, based on IRT aerial inspections, is deemed to be a powerful tool to detect the biogas production from a waste disposal site and to provide a preliminary estimation of the methane production potential.

5 References

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